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We have made progress on many fronts on the understanding and characterization of entanglement. Various new forms of bound (i.e. undistillable) entanglement have been introduced, as part of our work on unextendible product states. Cases of "superactivation" of bound entanglement, in which two different bound entangled states, when joined, produce distillable entanglement, have been established for four-party states and have been conjectured for bipartite states. These results show that the distillable entanglement is neither additive nor convex -- this achieves one of the major three year goals of this project. An explicit formula for the entanglement of formation was found for all isotropic mixed states. We discovered and characterized "remote state preparation", a generalization of quantum entanglement in which the transmitted quantum state is known to Alice. Very recently, with A. Winter, a new, more efficient protocol for RSP has been discovered.

We have continued to study many ideas for the simplication of the Kane approach to quantum computing, with the replacement of electron spin for nuclear spin. Important simplifications over the currently published device designs will be possible. We have worked out a scheme for the implementation of quantum computing, builing on the theory of decoherence-free subspaces, that uses only the Heisenberg exchange interaction, or only the XY interaction. We have provided detailed calculations of how g-factor engineering could be realized in III-V semiconductor heterostructures. We have shown how to ameliorate the effects of spin orbit interaction in quantum-dot qubits. We have begun master-equation modeling of superconducting qubits.

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- G. Burkard, D. Loss, and D. DiVincenzo, "Coupled quantum dots as quantum gates," Phys. Rev. B 59, 2070 (1999).
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- B. M. Terhal and D. P. DiVincenzo, "Classical simulations of noninteracting-fermion quantum circuits," quant-ph/0108010.
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- D. P. DiVincenzo, D. W. Leung, and B. M. Terhal, "Quantum data hiding," quant-ph/0103098, accepted for publication by the IEEE Trans. Info. Theory.
- C. H. Bennett, J. I. Cirac, M. S. Leifer, D. W. Leung, N. Linden, S. Popescu, and G. Vidal, "Optimal simulation of two-qubit Hamiltonians using general local opoerations," quant-ph/0107035.

II. Scientific personnel: C. H. Bennett, D. P. DiVincenzo, J. A. Smolin, B. M. Terhal (postdoc), D. Leung (postdoc).

IV. Scientific Progress:

Theory of Entanglement—We have made progress on many fronts on the understanding and characterization of entanglement. Various new forms of bound (i.e. undistillable) entanglement have been introduced, some obtained by our new proofs on the existence of various unextendible product bases. Cases of "superactivation" of bound entanglement, in which two different bound entangled states, when joined, produce distillable entanglement, have been established for four-party states and have been conjectured for bipartite states. These results show that the distillable entanglement is neither additive nor convex. New explicit protocols for bipartite and multipartite distillation were introduced. On the other side, we obtained new evidience in 2000 that the entanglement of formation is additive. An explicit formula for the entanglement of formation was found for all isotropic mixed states. Constraints were obtained on the cardinality of optimal (minimal entanglement) decompositions of mixed states. We introduced the Schmidt number as a new measure of entanglement.

Quantum Communication Protocols--We obtained three new results in this area in 2000. We discovered and characterized "remote state preparation", a generalization of quantum entanglement in which the transmitted quantum state is known to Alice. We have determined the minimal entanglement and classical-channel resources needed for RSP. We have introduced the "quantum Vernam cipher", in which shared entanglement is used to implement a securely recyclable one-time pad. And we have introduced various prototcols for the interconversion between different forms of quantum entanglement by local operations. In 2001 we finished a major work on the characterization of interconversions between states in a multipartite setting. There has been significant progress on entanglement-assisted channel capacity, and on the quantum reverse shannon theorem. We have also studied the simulation of one two-body Hamiltonian by another, a result which illustrates that their entangling power is a key parameter in these simulations. There has recently been exciting new results on remote state preparation, indicating, to our surprise, that standard quantum teleportation is *not* optimal for the transmission of states from Alice to Bob if Alice knows the quantum states. This represents a novel application of Winter's method of noiseless coding of POVM measurements.

Physical Implementations and Phenomenology— We have continued to study many ideas for the simplication of the Kane approach to quantum computing, with the replacement of electron spin for nuclear spin. Important simplifications over the currently published device designs will be possible. We have worked out a scheme for the implementation of quantum computing, builing on the theory of decoherence-free subspaces, that uses only the Heisenberg exchange interaction. We have provided detailed calculations of how g-factor engineering could be realized in III-V semiconductor heterostructures. We have investigated the spins of electrons in quantum wires as a new kind of flying qubit. New algorithms have been proposed

for the universal simulation of Markovian quantum dynamics. And, in NMR, a new protocol for quantum process tomography has been worked out. More recently, we have shown that linear Fermion optics can be efficiently simulated by a classical computer, which is quite different from the boson case (which gives the full power of quantum computation).
Cryptography--At the beginning of this program, we discovered "nonlocality without entanglement", which indicated that there would be a way to do secret sharing with joint quantum states. Recently we discovered how this could actually be accomplished ("secret sharing using Bell states") and we have made precise calculations of the level and kind of security achieved. In quantum-dot qubits, we have proposed a cavity QED implementation. This implementation has the XY interaction as the fundamental two-body interaction, and we have recently shown theoretically how this interaction (and the Heisenberg interaction, appropriate for the single-electron quantum dot quantum bit) can be used efficiently to implement quantum computation.
Reviews—We have written a couple of major overviews on the use of quantum computing tools for the solution of a wide range of information processing tasks, on the prospects for spin-based solid state quantum computation, and a general overview of the field (published in Nature) A plenary presentation and paper were given at the International Electron Device Meeting on the prospects for semiconductor quantum computers. A keynote article was written for a special issue on the physical implementation of quantum computation was written, reviewing the five criteria for the physical implementation of quantum computation.

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